Date: December 8, 2014

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cc: Daniel Chang, Groundwater Program Supervisor

Subject: Assessing the Risk That Fuel Released From the Red Hill Fuel Storage Facility Poses to Drinking Water Sources

This memorandum lays out a coordinated approach to evaluating the risk that past, current, and future fuel releases at the Red Hill Fuel Storage Facility (the Facility) pose to groundwater and may pose to public drinking water sources. Much of what is proposed here is already under consideration. This memorandum puts in a single document the different tests, data, and procedures that taken together can best evaluate contamination risk from fugitive fuel releases. It also summarizes the rationale behind the suggested approach.

The question that we seek to answer is: "What is the impact of past, current, and future fuel releases on the quality the groundwater and in particular what is the chance that detectable contamination will be captured by a public drinking water well?". To answer this question the answer to a series of questions is needed that include:

1. What fraction of the fuel released will migrate to the water table?
2. Once at the water table how far and in what direction will the free product plume travel before it becomes immobile?
3. Once the free product plume has become immobile how far and in what direction will the dissolved contaminants travel before natural processes reduce the concentrations to benign levels?

It is not possible to develop complete answers for all of these questions. For example the transport of the free product in the unsaturated zone cannot be predicted with any certainty due to the great number of unknowns. But many of the important variables can be characterized and in many cases quantified by a comprehensive hydrologic investigation. Below is a summary the approach that is proposed:

a. Use available data to the evaluate to the extent possible those processes such as fuel migration in the unsaturated zone that are difficult to model or measure;
b. Perform a regional groundwater gradient study to identify the probable groundwater flow directions;
c. Perform regional aquifer tests using both the Halawa Shaft and Red Hill Shaft to test hydraulic connectivity between the Halawa shaft and the Facility;
d. Evaluate the chemical indicators of groundwater flow to identify contaminant flow paths;
e. Calculate the expected groundwater concentrations of the various contaminants in the fuels at the Facility for later estimates of retardation and degradation rates;

f. Do a preliminary analysis of the preceding data to design and execute a tracer test to verify groundwater flow pathways and measure the parameters necessary to estimate the contaminant retardation and degradation rates; and
g. Use the results of this comprehensive hydrologic investigation to calibrate and validate a groundwater contamination risk model.

The following pages provide more detail about the approach and lays out the rationale for each test.

An Approach to Evaluate the Regional Groundwater Flow in the Vicinity of the Red Hill Fuel Storage Facility and the Risk of Fuel Contamination to Public Drinking Water Sources

The question this investigative approach seeks to answer is: "What is the impact of past, current, and future fuel releases on the quality the groundwater and in particular what is the chance that detectable concentrations of contamination will be captured by a public drinking water well?". Data that is critical to answering this question can be gathered by performing the following steps:

a. Use available data to the evaluate to the extent possible those processes such as fuel migration in the unsaturated zone that are difficult to model or measure;
b. Perform a regional groundwater gradient study to identify the probable groundwater flow directions;
c. Perform regional aquifer tests using both the Halawa Shaft and Red Hill Shaft to test hydraulic connectivity between the Halawa shaft and the Red Hill Fuel Storage Facility (the Facility);
d. Evaluate the chemical indicators of groundwater flow to identify contamination flow paths;
e. Calculate the expected groundwater concentrations of the various contaminants in the fuels at the Facility for later estimations of retardation and degradation rates;
f. Do a preliminary analysis of the preceding data to design and execute a tracer test to verify groundwater flow pathways and measure the parameters necessary to estimate the contaminant retardation and degradation rates; and
g. Use the results of this comprehensive hydrologic investigation to calibrate and validate a groundwater contamination risk model.

Use available data to the evaluate to the extent possible those processes such as fuel migration in the unsaturated zone that are difficult to model or measure

Movement of fugitive fuel in the unsaturated zone is a complex question that cannot be answered with any certainty. The processes are too complex and the available data are just too sparse. For example, the primary direction of fuel will be downward making the vertical permeability of the lava formation an important parameter to quantify. Nearly all of the available permeability tests (or hydraulic conductivity if water is the fluid of interest) have evaluated the horizontal permeability using pumping tests. In numerical models a ratio of vertical to horizontal permeability of 1:100 or 1:200 is assumed but has not been rigorously tested. This is not problem when evaluating saturated flow since the vertical flow component is negligible compared the horizontal flow component. But in assessing the migration of fuel in the unsaturated zone knowing both the vertical and horizontal permeabilies are important. Critical data that are also needed but not available include:

- The volume of dead-end pore space (e.g. vesicles on the surface of the rock and clinker zones that get pinched out between massive lava layers);
- Aperture width of the factures since three phases are competing for this space (vapor, water, and oil); and
- Residual water content in the unsaturated zone (highly variable due to recharge).

However some insight can be gained from available data. The theoretical maximum water solubility of JP-5 and JP-8 ranges from about 4,000 to 5,000 μg/L and is the basis of the THP SSRBL of 4,500 μg/L. During the first round of groundwater sampling after the fuel release was reported, the TPH-d concentration at RHMW02 was about 5,000 μg/L indicating free product in close proximity to RHMW02 or a pulse fuel saturated recharge to the water table (Figure 1). Either way it implies that fluid that moved through the leaked fuel arrived at the water table shortly after the release. This is reasonable since there are no soil or ash layers to break the network of inter-connected fractures between the site of the leaks and the water table. Soil vapor data (Figure 2) implies that, although there was an initial fast-path for fluid to the water table after the fuel release, there was also a significant amount of fuel held in the zone surrounding the tank that did not migrate past the soil vapor probes until April and later. There are structural controls on the path the free product in the unsaturated zone will take. Basic geology can be used since the dip direction of the lava bedding will control free product migration and may have resulted in a fuel migration path away from RHMW02 and RHMW01 as evidenced by the lack of any free product detection by the oil-water interface measurements.

Again a review available data can provide insight to what has occurred in the unsaturated zone. The groundwater gradient can help define the most likely migration path for the fuel that has or may reach the water table. Continued oil-water interface measurements in the tunnel and at the sentinel wells will aid in confirming the presence and migration of free-product. It may be possible to identify large accumulations of free-product on the water table using geophysical techniques. However, application of geophysical techniques is likely not cost effective unless there are indications that a large accumulation of free product exists.

Perform a regional groundwater gradient study to identify the probable groundwater flow directions

The groundwater flow directions of concern have a local component consisting of that water captured by the Red Hill Shaft and a regional component that includes all of the water that flows beneath the facility from the point of origin to points of discharge (i.e. capture by a well or stream, or submarine discharge into the ocean). The entire flow path does not need to be characterized since the points of concern are the Facility and down gradient receptors. However, enough of the flow path needs to be characterized to evaluate whether or not there is a risk to receptors (primarily drinking water wells). The groundwater gradient computed by the 2007 RI Report only evaluated on site wells and computed a groundwater gradient in a direction of the Moanalua Wells. The 2010 Groundwater Gradient Study showed that the water table elevation was higher to the southeast of the Facility than to the northwest implying that groundwater flow toward the Moanalua Wells is probably not occurring. The measured groundwater gradient does imply possible groundwater flow from beneath the Facility toward the Halawa Shaft. However, a flow path exists only if there is hydraulic connectivity. The 2010 Groundwater Gradient Study needs to be validated and the hydraulic connectivity between the Facility and the Halawa Shaft evaluated.

A regional groundwater gradient study should include observation wells from east of the Facility to west of the Halawa Shaft. Figure 3 shows the locations of possible water level measurement points. The Top of Casing elevation of some of these wells has been measured multiple times giving different elevations. But no single all inclusive survey has been done. A precision GPS survey is the most cost effective method. This method was used for the 2010 Groundwater Gradient Study. The 2010 Groundwater Gradient Study can be improved upon by following the guidance of Dick Carlson of the U.S. Geodetic Survey. He recommends taking satellite data for at least 40 minutes at each point and repeating the data collection at a time of a different GPS satellite configuration. During the 2010 Groundwater Gradient Study each point was GPS'd only once for about 10 minutes. Mr. Carlson estimated the vertical accuracy of a GPS survey is about +/- 10 cm (+/- 0.33 ft). The uncertainty may sound excessive but it is important to note that in evaluating groundwater gradient it is not the absolute elevation that is important but rather the relative elevations of the points that are measured. There is quite a difference in groundwater elevation difference going from Moanalua to Halawa. According to the 2010 Groundwater Gradient Study, the groundwater elevation in the HBWS Manaiki Observation Well located between Moanalua and Kalihi Valleys was about 1.4 feet higher than that at the on-site monitoring wells and 2.6 feet higher than at the HBWS Halawa Observation Wells. These differences are significantly greater than accuracy uncertainty.

Perform regional aquifer tests using both the Halawa Shaft and Red Hill Shaft to test hydraulic connectivity between the Halawa shaft and the Red Hill Fuel Storage Facility

The assessment of the risk posed by contamination at the Facility includes characterizing the hydraulic connectivity between the groundwater that flows beneath the Facility and the critical receptors, specifically drinking water wells. The aquifer test conducted for the 2007 RI shows good hydraulic connectivity from the southeast side of Halawa Valley to the Kalihi Valley. The response at the HBWS observation wells on the northwest side of Halawa Valley to the pumping at the Red Hill Shaft was much less than that predicted by the numerical groundwater flow model indicating a possible barrier to groundwater flow in that direction. To northwest of Halawa Valley is the HBWS Halawa Shaft that is major drinking source for Oahu. Contamination of this source would be catastrophic to Honolulu's public water system. The hydraulic connectivity between the Facility and HBWS Halawa Shaft can be tested by repeating the aquifer test done for the 2007 RI. In this test, the responses at the observation wells to prolonged cycles of pumping and rest at the Halawa Shaft should be monitored. Pumping at the Red Hill Shaft should be minimized while testing the response to Halawa Shaft pumping. This test will have the added benefit of the two new sentinel wells located between the Facility and Halawa Shaft. The aquifer response to changes in pumping at the Halawa Shaft can be evaluated by numerical modeling as was done during the 2007 RI.

Evaluate the chemical indicators of groundwater flow direction and identify potential contamination flow paths

The primary purpose for evaluating the groundwater gradient is to identify groundwater flow paths; more specifically to identify the path that groundwater contamination will take so the probable receptors can be identified and remedial/mitigation measures taken if needed. The groundwater gradient analysis should be augmented by mapping the distribution of natural tracers. These tracers are also economical to analyze. The natural method includes evaluating the spatial distribution of dissolved species with an identified source area such as chlorides or species that are modified as they pass through a petroleum contaminated zone.

Microbes use dissolved organic contamination as an energy source. During their metabolism of organic compounds, heat, carbon dioxide, methane, and ferrous iron are produced. Dissolved oxygen, nitrate, and sulfate are consumed. Evaluating the spatial trends in these parameters can help locate centers of contamination and identify groundwater flow paths down gradient of the contamination. When evaluating the in-situ tracers it is important to consider that the Facility may not be the only source of organic contamination.

Tracers with identifiable source areas include:

- Chloride where areas of increased chloride concentration include dispersal of up-flow from the CWRM Deep Monitoring Well and groundwater in the Salt Lake area;
- Anthropogenic chemicals from a known location (none yet identified);
- Major ions distribution – usually plotted on Piper Diagrams such as was done for the Oil Waste Disposal Facility investigation in 2000 (see Figure 4).

Tracers modified during transport

- Electron acceptors that are consumed by natural attenuation get depleted down gradient from a contaminated area and include:
  - Dissolved oxygen, nitrate, and sulfate
- Species that are produced by natural attenuation are enriched down gradient from a contaminated area and include:
  - Ferrous iron, methane, and carbon dioxide (usually manifest as an increase in alkalinity);
- Groundwater temperature – natural attenuation is an exothermic reaction and does increase groundwater temperature

Calculate the expected groundwater concentrations of the various contaminants in the fuels at the Facility

Critical to assessing the rates and amount of natural attenuation is to identify the starting concentrations of the contaminants. The dissolved concentrations of the various compounds making up fuels can be estimated based on solubility and the mass fraction of the compounds in the fuel. These calculations were done for JP-5 fuel to develop the reactive transport parameters used for the fate and transport modeling done for the 2007 RI. It was intended that these calculations would be documented in an appendix to modeling report (Appendix M of the 2007 RI Report). However, in compiling the report these calculations were inadvertently left out. They are included as an appendix to this memorandum. Similar calculations were done for diesel and JP-8 in the *Soil Vapor Sampling Monitoring Analysis Letter Report* for diesel and JP-8 submitted to the Navy in 2010 by TEC, Inc. The petroleum hydrocarbon partitioning calculations provided the basis for the soil vapor SSRBL of 280,000 ppbv. The partitioning calculations provide the starting concentrations that will be used with the contaminant chemistry and the tracer test results to compute contaminant retardation and degradation.

Design and execute a tracer test to verify groundwater flow pathways and measure the parameters necessary to estimate the contaminant retardation and degradation rates

The optimum method of validating and improving the contaminant fate and transport model is with a tracer test. A network of monitoring wells at the Facility gives a tracer test a high probability of success. Properly conducted and analyzed a tracer test can provide the following critical information:

- Groundwater flow paths;
- Groundwater flow velocity; and
- The aquifer hydrodynamic dispersion characteristics.

The most important benefits of a tracer test are confirming the flow path that contamination will take and providing physical measurements of groundwater velocity that are needed to compute the rate of contaminant retardation and degradation. Retardation is the slowing of the contaminant transport relative to the movement of groundwater. The mechanism usually responsible for retardation is sorption of the contaminant onto the aquifer matrix.

The rate of contaminant degradation and transformation at a specific site is difficult to know with certainty. The anaerobic degradation rate for TPH at the Facility estimated by reactive transport modeling was 0.008 d^{-1}, but the bulk degradation rate (considering both aerobic and anaerobic degradation) was higher at 0.01 d^{-1}. The modeled degradation rate has not been validated with any field analysis. By knowing the groundwater velocity (as indicated by the tracer test) the combined effect of contaminant retardation and degradation can be estimated by comparing the contaminant concentration at the source to that at some other monitoring point along a flow path. The two values can be inserted into contaminant retardation and degradation equations to estimate the contaminant transport velocity (which is slower than the groundwater flow velocity) and rate of degradation. The tracer test will also give indisputable evidence of the path that contamination will take.

Use the results of this comprehensive groundwater contaminant transport investigation to calibrate and validate a groundwater contamination risk model

The use of a numerical-groundwater flow and transport model has been the method to assess risk to the drinking water sources and establish SSRBLs. The numerical modeling done for the 2007 RI Report is the best we have to date and was a comprehensive evaluation of the groundwater flow in the vicinity of the Facility. However, when the modeling was done for the 2007 RI Report the regional flow in the Moanalua, Red Hill, and Halawa area had not been well characterized. Of greater significance is that the risk to the Halawa Shaft had not been considered as seriously as later findings such as the 2010 Groundwater Gradient Study would indicate it should have been. A concerted effort was put into the transport modeling to provide an as accurate picture as possible of the role that natural attenuation plays in limiting the extent of contamination. However, this model was largely theoretical and was not validated with field data. Also contaminant data collected over the last 7 years indicates that Naphthalene compounds pose a greater contamination risk than does Benzene.

Future modeling should evaluate the transport and degradation characteristics of the Naphthalene compounds. Incorporating the data gathered by this proposed approach into the groundwater flow and transport model will provide a much stronger physical basis for the modeling and greatly reduce the uncertainty associated with the modeling. Reducing the uncertainty is of paramount importance for any risk evaluation such as Red Hill where there are many different organizations potentially affected by any groundwater contaminating events at the Facility.

Summary

This approach provides a framework to better use existing data, identify new data that should be collected, and how to use this data to characterize the groundwater flow and contaminant transport characteristics in the Moanalua, Red Hill, and Halawa areas. The goal of this approach is to evaluate the risk that fugitive fuel contamination from the Facility poses to groundwater and to public drinking water sources. Much of what is proposed in this memorandum is already being considered or planned. For example updating the numerical groundwater flow and transport models is planned. Modeling is most comprehensive method to evaluate risk. However, the model is only as good as the data upon which it is based. The data collected by this approach will aid in producing model results that are validated by a solid foundation of field work.

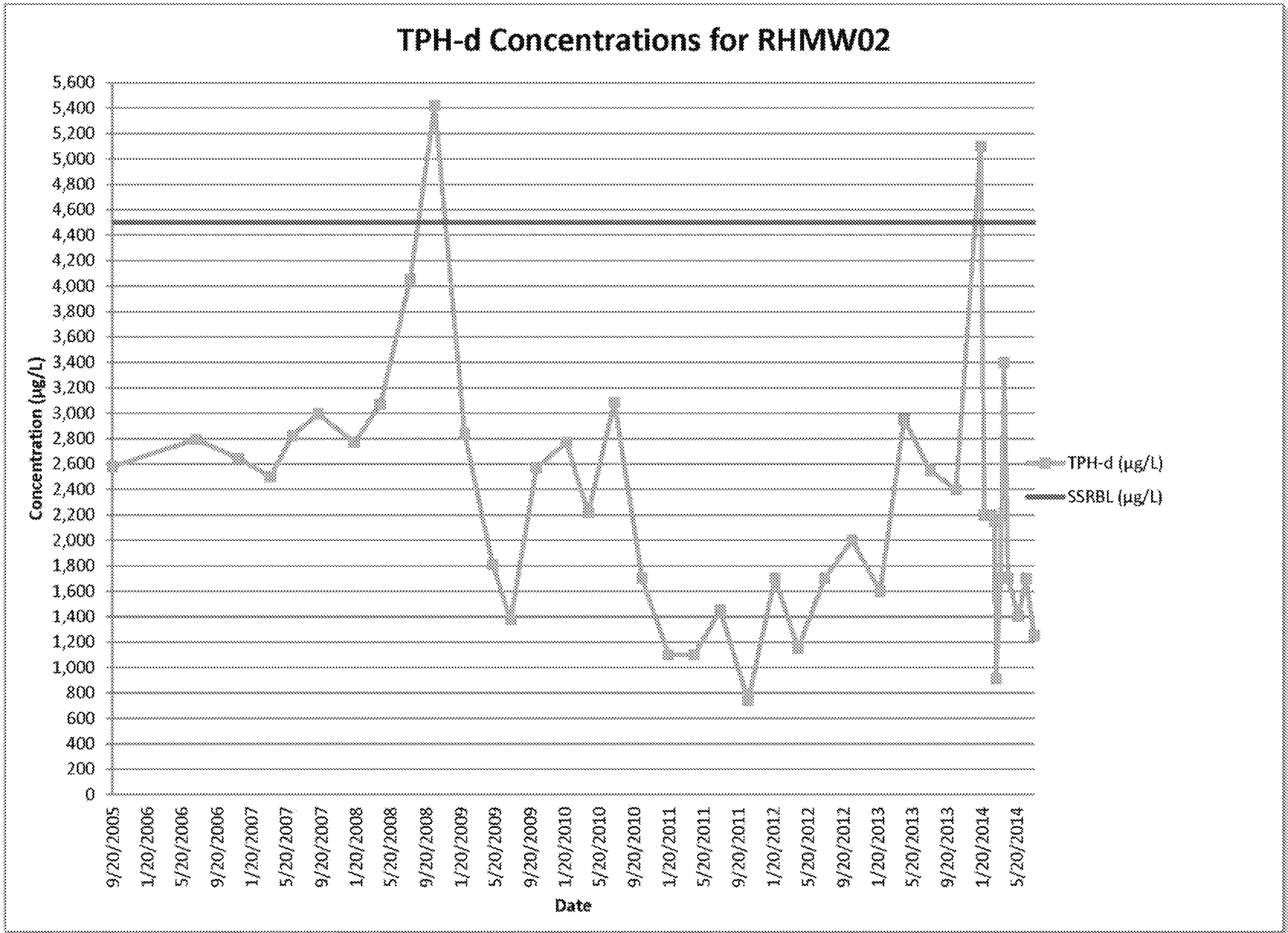

Figure 1. This graph, taken from the 3rd quarter groundwater modeling report compares the TPH-d concentrations to the SSRBL of 4,500 µg/L. The SSRBL is based on the theoretical maximum solubility of JP-5 fuel. An exceedance of the SSRBL indicates fuel in contact with the groundwater or a pulse of fuel saturated near the monitoring well.

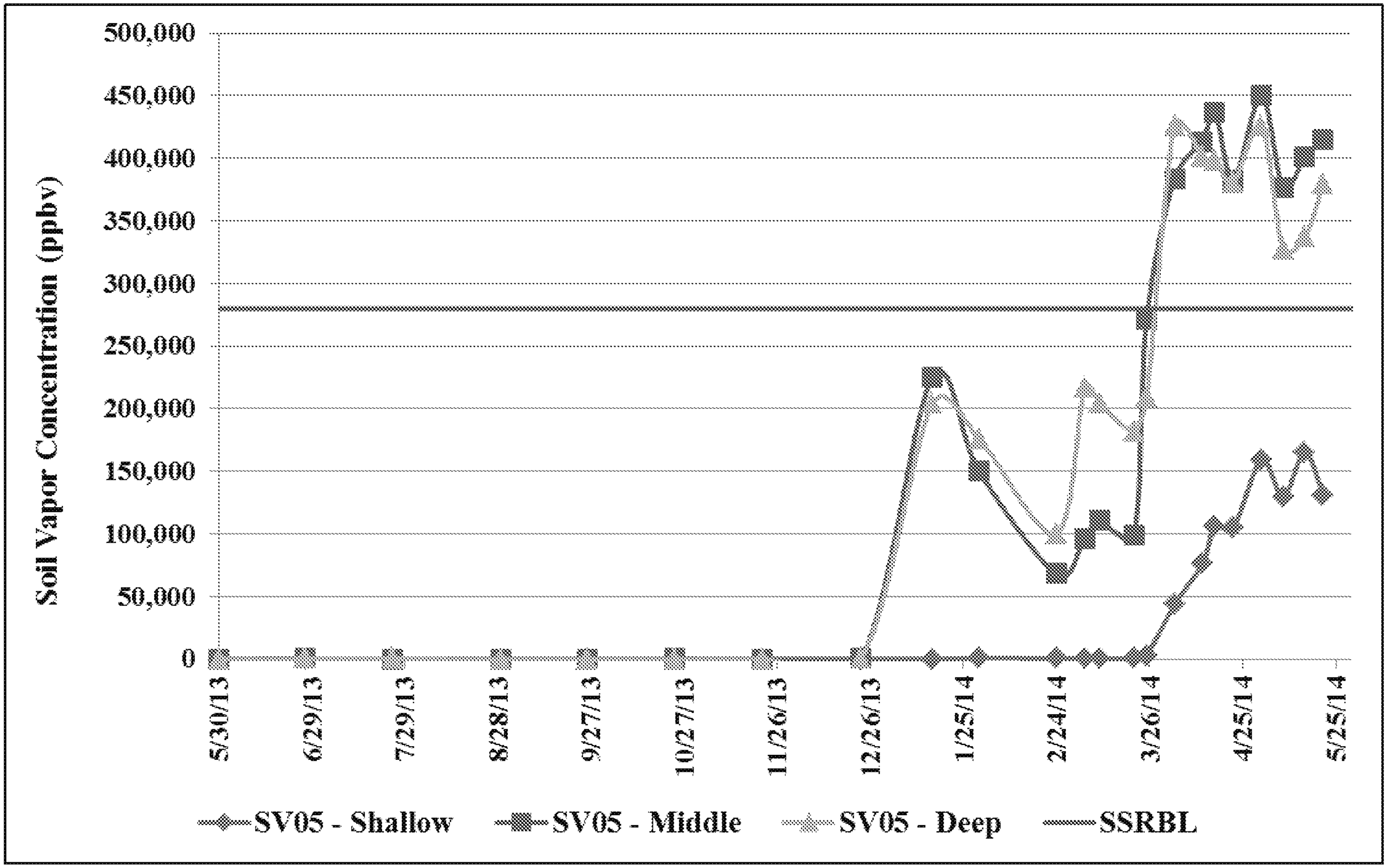

Figure 2. This graph compares the soil vapor readings from beneath Tank 5 from 5/30/13 to 5/30/14 with the SSRBL of 280,000 ppbv. This graph is a qualitative indicator of fuel or fuel saturated movement past the soil vapor probes.

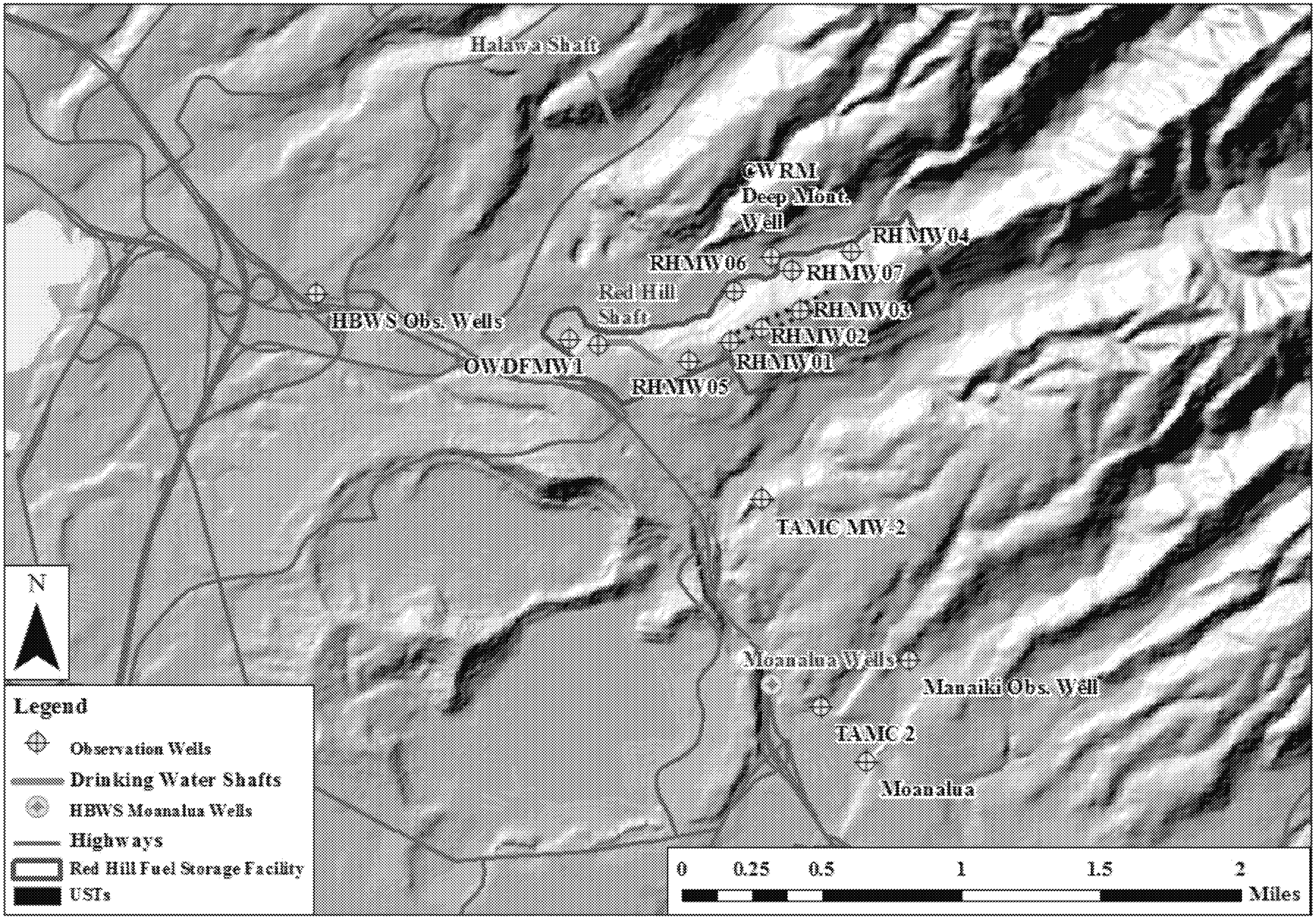

Figure 3. A map of the Moanalua, Red Hill, and Halawa areas showing the locations of the observation wells and drinking water sources that fall within the boundaries of the groundwater model documented in the 2007 Red Hill RI Report.

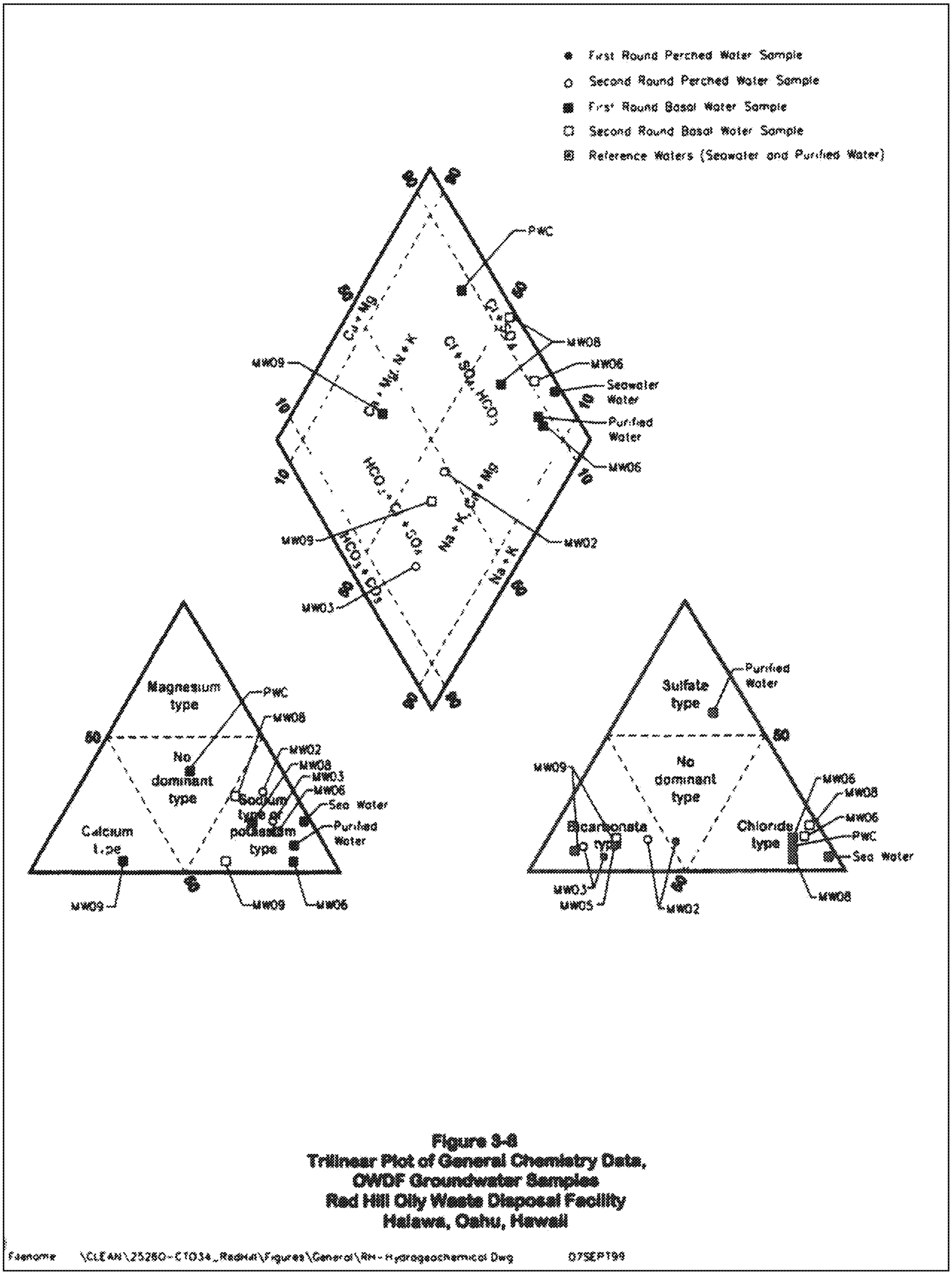

Figure 4. The above diagram is an example of a Piper Diagram that is used to evaluate trends in the major ion chemistry of water. This diagram is one method of identify chemical trends to evaluate groundwater flow paths.